PROGRESS TOWARD A PROTOTYPE RECIRCULATING ION INDUCTION ACCELERATOR

A. Friedman *H. C. Kirbie* *W. M. Sharp*
J. J. Barnard *B. G. Logan* *T. J. Fessenden*[†]
M. D. Cable *S. M. Lund* *D. L. Judd*[†]
D. A. Callahan *L. A. Nattrass* *S. Eylon*[*]
F. J. Deadrick *M. B. Nelson* *H. A. Hopkins*[‡]
D. P. Grote *M. A. Newton* *D. B. Longinotti*[**]
V. P. Karpenko *T. C. Sangster*

Introduction

The U.S. Inertial Fusion Energy (IFE) Program is developing the physics and technology of ion induction accelerators, with the goal of electric power production by means of heavy ion beam–driven inertial fusion (commonly called heavy ion fusion, or HIF). Such accelerators are the principal candidates for inertial fusion power production applications, because they are expected to enjoy high efficiency, inherently high pulse repetition frequency (power plants are expected to inject and burn several fusion targets per second), and high reliability. In addition (and in contrast with laser beams, which are focused with optical lenses) heavy-ion beams will be focused onto the target by magnetic fields, which cannot be damaged by target explosions. Laser beams are used in present-day and planned near-term facilities (such as LLNL's Nova and the National Ignition Facility, which is being designed) because they can focus beams onto very small, intensely illuminated spots for scaled experiments and because the laser technology is already available.

LLNL has participated in HIF research since its inception and has worked on HIF target physics and fusion-chamber beam-propagation physics, accelerator physics and technology, and advanced power-plant concepts. Here we discuss a newly initiated experimental effort aimed at developing a low-cost approach to high-current heavy-ion acceleration, based on recirculation of the ion beams.

An induction accelerator works by passing the beam through a series of accelerating modules, each of which applies an electromotive force (emf) to the beam as it goes by; effectively, the beam acts as the secondary winding of a series of efficient one-turn transformers. Each of these transformers requires a sizable ferromagnetic toroid, or core. The cores must be large enough to sustain enough volts of emf for long enough to impart the required impulse to the entire beam. In the recirculating induction accelerator, or recirculator, the beam is repeatedly passed through the same set of accelerating cores and focusing elements, thereby reducing the length of the accelerator and the number of cores and magnets required. In a recirculator, it is not necessary to accelerate the beam quickly to minimize length and cost, as is the case in a linear accelerator, or linac; acceleration can be more gradually, over many laps, and this allows the cores to be made smaller and less expensive (the required voltage is lower). This promises a very attractive driver cost if the technical challenges associated with recirculation can be met.

The recirculator concept as it applies to an ICF driver was presented in two previous *ICF Quarterly* articles,[1–2] and elsewhere[3]; another recent article[4] describes LLNL's work on a pulse modulator for use in a recirculator. Figure 1 shows an artist's conception of an IFE power plant driven by an induction recirculator.

We present plans for and progress toward the development of a small (4.5-m-diam) prototype recirculator, which will accelerate singly charged potassium ions

[†]Lawrence Berkeley Laboratory, Berkeley, California
[*]Titan Beta, Dublin, California
[‡]U. C. Berkeley, Berkeley, California
[**]EG&G, Inc., Pleasanton, California

(atomic weight 39 u) through 15 laps, increasing the ion energy from 80 to 320 keV and the beam current from 2 to 8 mA. Beam confinement and bending are effected with permanent-magnet quadrupoles and electric dipoles, respectively. The design is based on scaling laws and on extensive particle and fluid simulations of the behavior of the space charge–dominated beam. The dimensionless beam dynamics parameters were chosen to resemble those of a driver; the experiments should serve to validate major elements of the recirculator concept.

This Small Recirculator is being developed in a build-and-test sequence. An injector and matching section are operational, and we are already investigating intense-beam transport in a linear magnetic channel. Near-term plans include studies of space charge–dominated beam transport around a bend. Later we will study insertion and extraction of the beam into and out of the ring, and acceleration with centroid control. The ultimate goal is demonstration of flexible recirculator operation.

In contrast with conventional rf-driven accelerators, the beam in the Small Recirculator experiments is space-charge dominated. That is, the transverse force balance is a near-cancellation of the applied confining force and the beam's self-induced electrostatic expanding force; thermal pressure plays only a minor role. Effectively, the beam is a non-neutral plasma in nearly laminar flow. The fully operational Small Recirculator will confine and accelerate many more ions than a conventional circular accelerator of this scale and beam energy.

Recirculator Concept

A recirculating induction accelerator is expected to cost considerably less than a conventional ion-induction linac. The overall accelerator length is reduced—by a factor of ~2 to 3, to about 3.6 km (and possibly shorter) in the "C-design" recirculator of Ref. 3. The accelerating cores are smaller, because acceleration can be slower. Research on recirculator drivers has centered on four-beam multi-ring designs, in which each ring increases the beam's energy by an order of magnitude over 50 to 100 laps. In contrast with most HIF induction linac concepts,[5] recirculator designs considered to date do not use beam merging. Hybrid designs (with a recirculator at the low-energy end and a linac at the high-energy end) are also possible and may prove attractive.

The beam-dynamics issues that must be resolved before a recirculating driver can be built include centroid control, longitudinal control, and beam insertion and extraction. Beam compactness must be preserved throughout, so that the beam can eventually be focused onto a small spot. The critical measure in this context is compactness in the 6-D phase space of particle positions and velocities. Accelerator researchers commonly use a measure of compactness called emittance, which is the area occupied by the beam in a two-dimensional projection of that 6-D phase space. For example, the horizontal transverse emittance ε_x is the area occupied by particles in the space (x,x'), where x is the horizontal coordinate normal to z (the mean direction of beam motion) and x' is the velocity along that coordinate normalized to the velocity along z, *i.e.*, the angle between a particle's velocity and the local mean velocity. For many purposes the normalized emittance $\varepsilon_\mathrm{n} = \beta\gamma\varepsilon$ is used, where β is the particle speed normalized to the speed of light and $\gamma = (1 - \beta^2)^{-1/2}$. The normalized emittance enjoys the property of being conserved during acceleration if no nonlinear (with respect to the individual coordinates) forces act on the beam. Of course, some nonlinearity is always present in real accelerators, so some emittance growth will in general occur, but the concept of normalized emittance remains useful.

As described below, beam-dynamics issues can be addressed at reduced scale in a small prototype recirculator. The waveform generators in a driver must supply variable accelerating pulses at repetition frequencies of

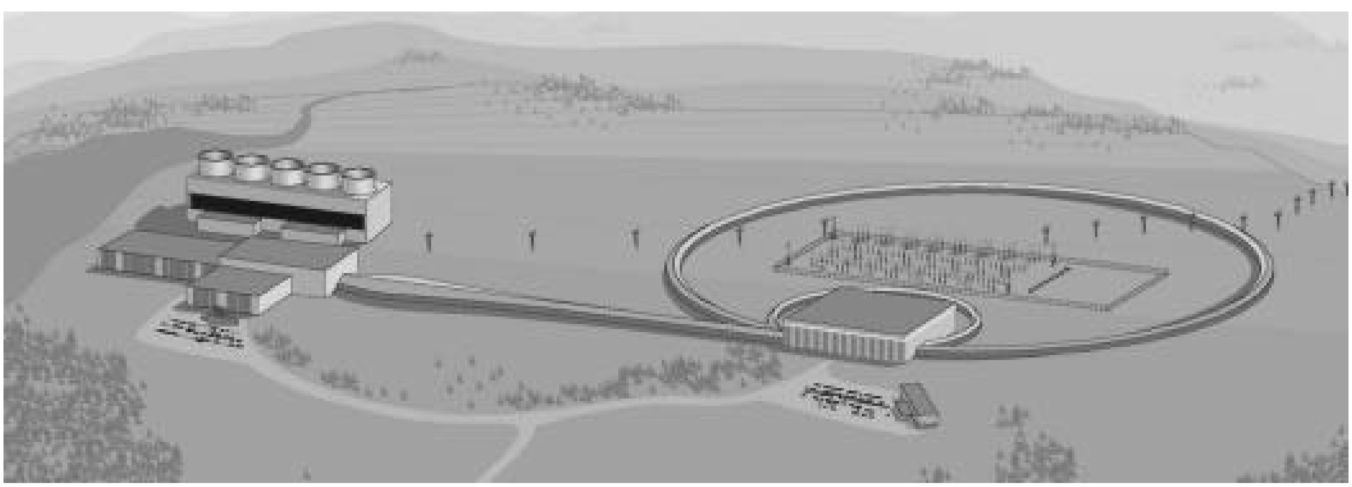


FIGURE 1. Artist's rendering of recirculator-driven power plant. (05-00-1194-3846pb03)

~50 kHz and must supply accurate time-varying dipole fields with good energy recovery. These requirements are challenging, but advances in solid state power electronics should make it possible to meet them through a technology development program. Present technology has achieved 200-kHz bursts at 5 kV and 800 A with pulse durations of 0.5 to 2 ms, but with a nonvariable format.[6] Because of its long (~200 km) beam path length, and because the beam repeatedly visits each section of the beam line, a recirculator driver will require a vacuum of ~10^{-10} to 10^{-11} Torr.

Design of the Small Recirculator

LLNL is developing a small prototype ion recirculator in collaboration with LBL, EG&G, and Titan-Beta. This Small Recirculator will be assembled and operated as a series of experiments over several years. Figure 2 illustrates the overall physics design of the Small Recirculator and lists some of the elements that must all work together in the Small Recirculator and in a full-scale fusion driver.

The Small Recirculator will have a circumference of 14.4 m, a 3.5-cm aperture (pipe) radius for the beam-confining (commonly called focusing) and beam-bending elements, and a 72-cm lattice period (segment of the repetitive lattice of focusing and bending elements). The beam will be transversely confined by permanent-magnet quadrupole lenses with a field of ~0.294 T at the pipe wall, and will be bent with electric dipole deflector plates. These quadrupoles and dipoles will each physically occupy about 30% of the axial lattice length, and the full recirculator ring will consist of 40 half-lattice periods, including one or two periods using special large-aperture quadrupole magnets through which the beam will be inserted and / or extracted. The fundamental building block is actually the 36-cm half-lattice period, but the polarity of the quadrupole lenses is reversed in each alternate half-lattice period; this provides so-called alternating-gradient or strong focusing as in most modern particle accelerators.

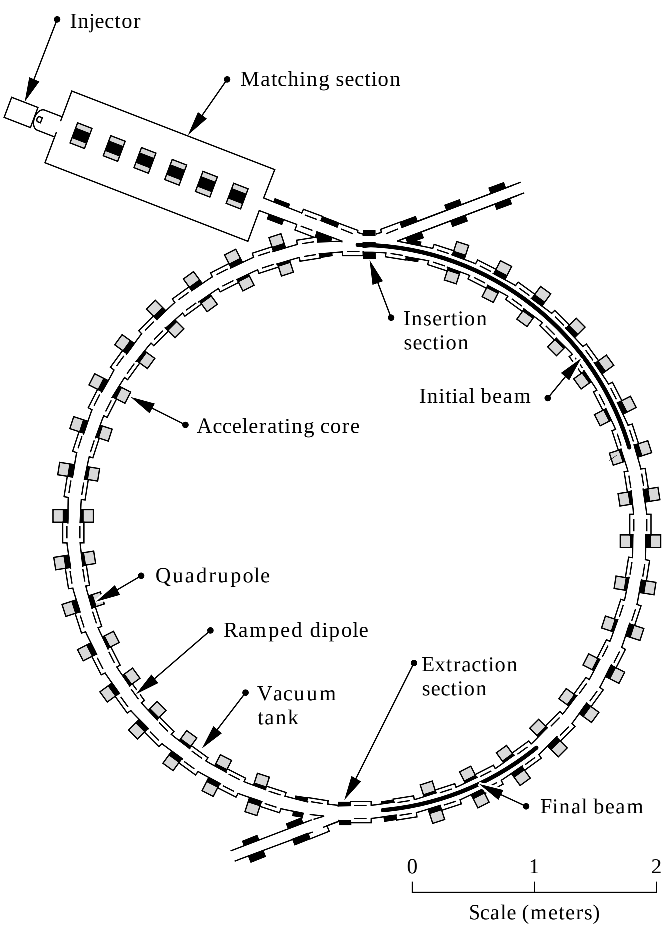


FIGURE 2. Final configuration of the Small Recirculator. (30-00-0695-1644pb01)

The K^+ beam ions will be accelerated from an initial kinetic energy of 80 keV to 320 keV over 15 laps by 34 induction cores (no induction cores will be present in the lattice periods where the beam is inserted and extracted). The initial beam current will be 2 mA, corresponding to a line-charge density of 3.6 nC / m and a characteristic beam radius of 1.1 cm, and the initial pulse duration will be 4 µs. After 15 laps of acceleration, the beam current will have increased to 8 mA, the line-charge density will be 7.21 nC / m, the average beam radius will be 1.3 cm, and the pulse duration will be 1 µs.

Because the quadrupole magnets provide a transverse restoring force to confine the beam, the beam centroid will, if displaced off-axis, oscillate back and forth across the centerline of the beam pipe. Over a full oscillation, the phase of the displacement will sweep through 360°. The initial phase advance of these “betatron oscillations” per lattice period of beam motion will be $\sigma_0 = 78°$. Thus a beam-centroid oscillation will require 360° / 78° ≈ 4.6 lattice periods, or about 4.6 / 20 = 23% of the circumference of the ring. Individual particles also execute betatron oscillations back and forth within the confines of the beam, but the frequency of these oscillations is lower than the “undepressed” frequency because the net focusing force is reduced by the repulsive effects of space charge, which (if unopposed) would blow up the beam. Initially, the net effect is a phase advance depressed to $\sigma = 16°$ by space charge. After 15 laps of acceleration, the phase advances will decrease to $\sigma_0 = 45°$ and $\sigma = 12°$. These parameters were chosen to resemble those of a driver-scale recirculator, although of course the latter would have many more betatron oscillations per lap.

Because the heavy-ion beam in the Small Recirculator is nonrelativistic and accelerating, obtaining the variable-format accelerating and bending waveforms will be technologically challenging. Those waveforms will require the accurate synthesis of detailed voltage pulses with repetition rates rising from about 40 kHz at the initial beam energy to 90 kHz at the final beam energy.[4,7] The voltage pulses for the electric dipoles must be correctly ramped in concert with the increasing beam energy. Properly shaped “ear” pulses must be applied at the beginning and end of the main pulses to provide longitudinal confinement, and lap-to-lap variation of the pulse duration and shape must be added to the accelerating waveforms to maintain or decrease the beam length.

To switch the beam into or out of the ring, time-varying dipole (bending) fields must be applied. Transverse confinement of the beam must be carried out during insertion or extraction. Our design uses a permanent-magnet quadrupole with an expanded aperture. Figure 3 shows the physics design of the insertion / extraction section. The main ring runs along the lower part of the figure; the insertion line (which brings the beam from the matching section into the ring) comes in from the upper left, and the extraction line runs toward the upper right. The beam trajectory is shown as it will appear during extraction.

Mechanical design of the Small Recirculator was challenging because of the necessity of fitting bending, focusing, and accelerating elements, as well as provisions for vacuum pumping and beam diagnostics, into each half-lattice period. Figures 4 and 5 show the nearly complete computer-aided design, as rendered by the CAD software.

Recirculator Modeling

Because the space charge–dominated beams in an induction accelerator are effectively non-neutral plasmas, theoretical and computational modeling of these beams is carried out using techniques related to those used in the accelerator and plasma physics communities. Models used range from simple zero-dimensional codes based on analytically derived scaling relations, through fluid- and moment-equation simulations, up to large and elaborate discrete-particle simulations.

The CIRCE code[8] is a multidimensional model that solves an envelope equation (evolving moments such as centroid position and transverse extent) for each of a number (typically a hundred or greater) of transverse beam “slices,” each at different longitudinal positions. The longitudinal dynamics of the beam is modeled by evolving the positions and velocities of the slices using fluid equations. CIRCE is used to assess alignment tolerances, accelerating schedules, and steering techniques in linacs and recirculators. It is useful for any application in which the evolution of the detailed internal degrees of freedom of the beam (e.g., emittance growth processes) need not be resolved; at present, beam normalized emittance is assumed constant in CIRCE.

Because the beam resides in the accelerator for relatively few plasma oscillation periods, particle-in-cell

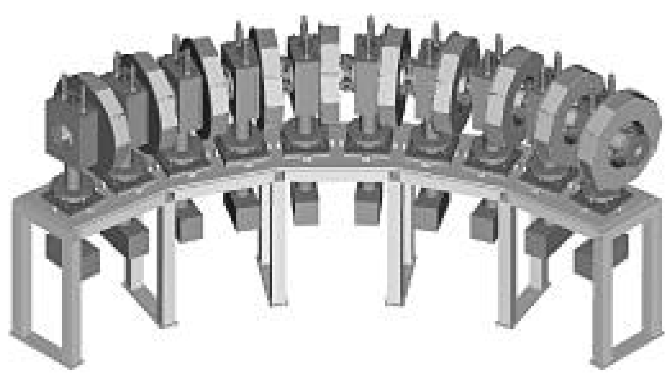
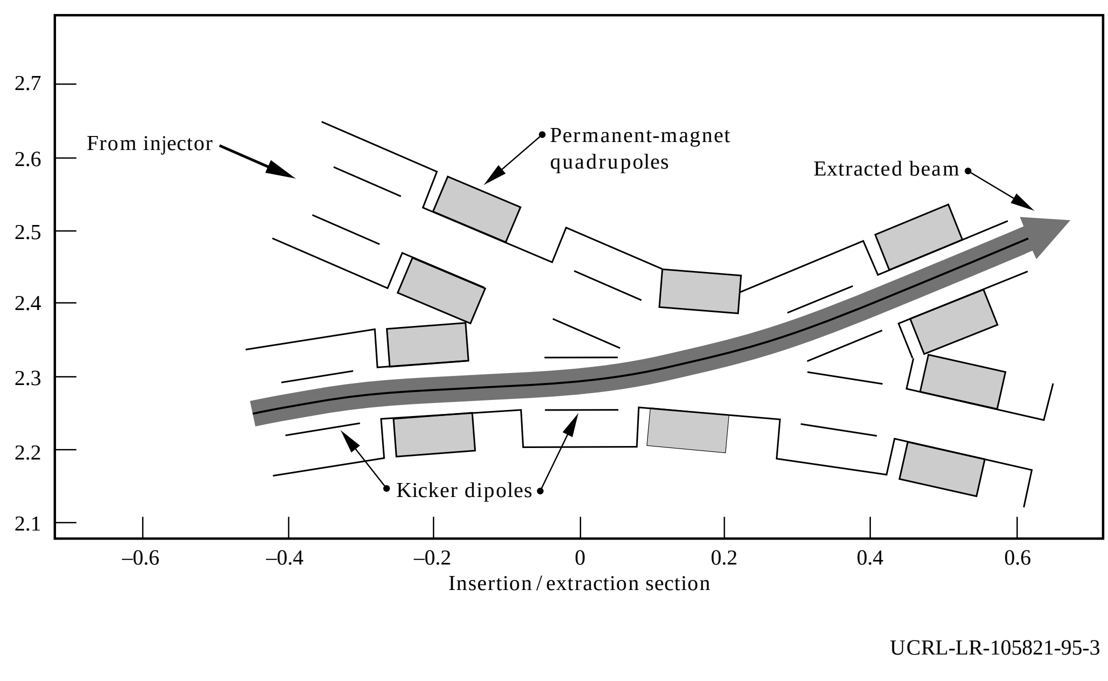


FIGURE 4. One-quarter of the Small Recirculator (CAD rendering). (30-00-0695-1649pb01)

FIGURE 3. Insertion / extraction section. (30-00-0695-1646pb01)



(PIC) simulation techniques are especially effective and have been invaluable in the design and analysis of experiments and in the prediction of the behavior of future machines. The WARP code includes fully three-dimensional (WARP3d)[9] and axisymmetric (WARPrz)[10] PIC simulation models. WARPrz is used for long-term beam dynamics studies, including the effects of accelerating module impedance. WARP3d is heavily used for "near–first principles" studies of accelerator elements and experiments.

Several novel techniques make WARP3d both accurate and efficient. These include capabilities for subgrid-scale placement of internal conductor boundaries and for simulating "bent" accelerator structures, as well as a technique for rapidly following particles through a sequence of sharp-edged accelerator lattice elements, using a relatively small number of time steps while preserving accuracy. On some problems, WARP3d is run in a quasi-steady state mode, which permits the completion of a 3-D run in just a few minutes of computer time; this makes it suitable for iterative design calculations. The ultimate goal of this code development is effective simulation of present-day experiments and of an HIF driver, from the source through the final focus, with a link from WARP into the codes used to model propagation in the fusion chamber and ultimately into the target design codes.

A number of other PIC codes employ a "slice" description of the beam (assuming slow variation of quantities along the beam); much application, as well as detailed studies of the properties of such PIC models of beams and plasmas, has been carried out.[11]

Emittance growth can result from the nonuniform distribution of beam space charge resulting from the action of centrifugal forces. As revealed in particle simulations using WARP3d[9] and interpreted theoretically,[12] growth occurs at changes in the accelerator's curvature where the distribution of beam particles relaxes toward a new equilibrium. A circular recirculator is therefore to be preferred over one with an elongated "racetrack" shape. Since the Small Recirculator is effectively circular (the changes of curvature that occur within a single half-lattice period are too rapid to matter), the only significant changes in curvature occur during insertion and extraction. The electric dipoles also introduce field aberrations. Detailed 3-D simulations show that proper shaping of the dipole plates should render the beam distortion minimal. We have studied the behavior of the beam in the Small Recirculator in some detail using CIRCE and WARP. A measurable amount of emittance growth is expected to take place over the 15 laps, mostly in the first two laps.[13]

Here we show the results of a WARP3d simulation of the beam in the Small Recirculator. For reasons of economy, the simulated beam is often made shorter than the actual beam will be. Figure 6 shows top and side views of the beginning of the simulation; the final

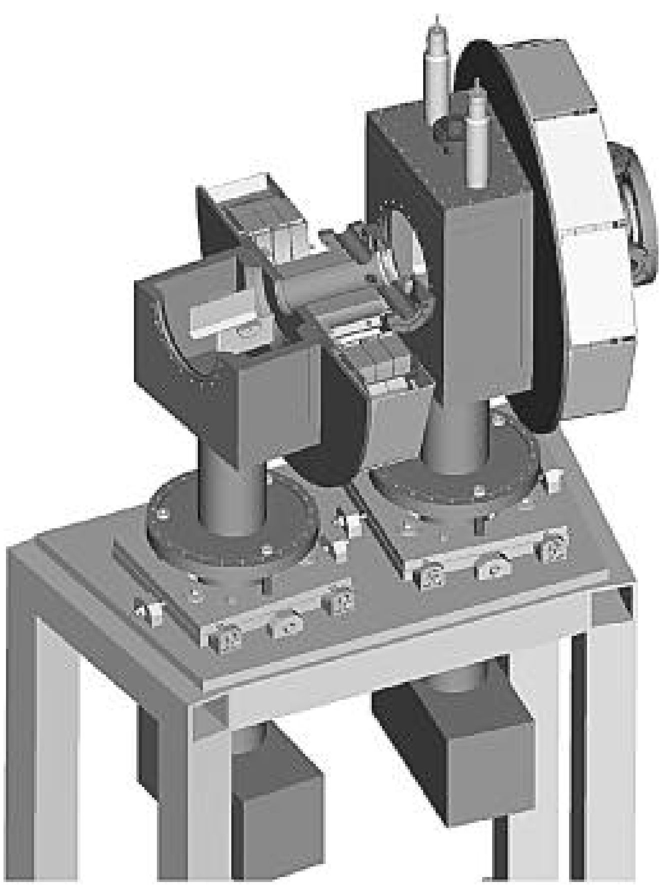


FIGURE 5. Two half-lattice periods of the Small Recirculator (CAD rendering). The top of the left-hand half-lattice period is cut away to reveal the internal structure. (30-00-0695-1650pb01)

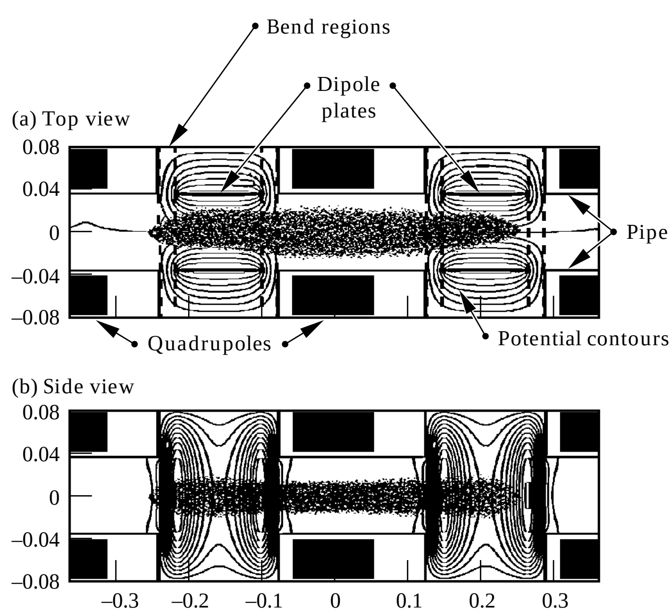


FIGURE 6. Top and side views of Small Recirculator beam simulated using WARP3d. "Bends" are shown straightened. (30-00-0695-1656pb01)

beam is very similar. Figure 7 shows the evolution of the emittance at mid-pulse; in this case, the beam length is kept roughly constant. After the initial jump arising from the transition to the bent lattice, there is little emittance growth over the 15 laps.

Experiment Plans

Linear experiments now getting under way will measure space charge–dominated beam quality after transport through a permanent-magnet quadrupole lattice, characterize the beam before injection, provide a test bed for diagnostic development, and afford a preliminary assessment of the role of electrons in magnetic beam transport (see Fig. 8).

The next experiments will study beam transport around a bend of order 90° (at first without any accelerating modules). The transition of the beam from a straight transport line into the ring will represent a change of curvature, and will allow us to study the resulting emittance growth. Emittance growth can also result from imperfections in the focusing and bending fields; the small imperfections expected in our experiments will be well characterized by theory and measurement. Even over a short bend, detailed intercepting beam diagnostics (using a two-slit apparatus to measure both transverse ion position and velocity) should be able to detect relatively small changes in the distribution of beam particles as a result of the bend. An important goal of these initial experiments will be validation of the computer models and scaling laws used to predict the behavior of linear and recirculating drivers.

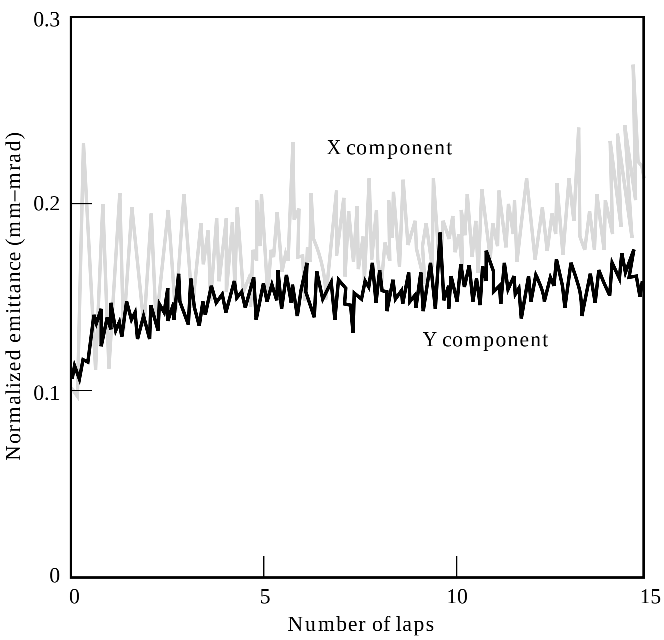


FIGURE 7. Time dependence of normalized beam emittance at mid-pulse for X (in-plane) and Y (out-of-plane) components. (30-00-0695-1658pb02)

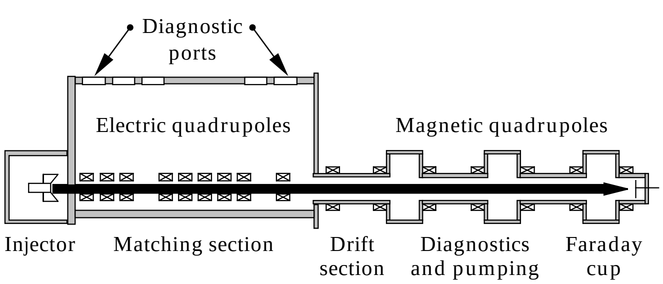


FIGURE 8. Linear configuration (length 4.568 m from source to final Faraday cup). (30-00-0695-1657pb01)

Later experiments will study insertion and extraction, acceleration (at first in a partial ring to facilitate measurement of the beam using intercepting diagnostics), beam steering, bunch compression, and fully integrated operation of the recirculator. Preservation of a small emittance will again be the central beam-physics issue to be addressed.

Until the ring is complete it will be possible to use intercepting diagnostics to characterize the beam and to calibrate the nonintercepting diagnostics that will be critical to the successful operation of the full ring. As currently planned, the ring will incorporate two extraction sections 180° apart, so the extracted beam can be diagnosed with detailed intercepting diagnostics twice each lap. As with earlier linac experiments at LBL, excellent shot-to-shot repeatability is anticipated and, so far, observed. The principal nonintercepting diagnostic under development is a segmented capacitive pickup to be located inside the quadrupoles.[14] The long duration of beam residence in the machine (up to, and possibly exceeding, 300 full lattice periods) will provide a unique opportunity to observe and characterize the longitudinal propagation of space-charge waves along the beam. Such waves will be launched (deliberately or otherwise) by mismatching the applied ear fields. The Small Recirculator will afford the longest beam path length of any near-term HIF research facility, and so will be able to explore issues such as slow thermalization that are important to both recirculating and linear drivers.

Status and Initial Results

The injector diode,[15] matching section, and straight experiment have been fabricated and are now operating; Fig. 8 shows the layout. Fifteen permanent-magnet quadrupoles have been procured; seven are being used in the straight experiment (see Fig. 10). A shorter line will serve as the link from the matching section to the ring. As shown in Figs. 4 and 5, the mechanical design of the half-lattice period is nearly complete.[16]

The electrostatic-quadrupole matching section (Fig. 8) gives the circular beam that leaves the diode an elliptical cross section suitable for alternating-gradient transport in the transfer line and the recirculator. A section of the Single Beam Transport Experiment (SBTE) apparatus from LBL was adapted by EG&G to serve this function. The potentials applied to the various quadrupole elements to obtain a matched beam were derived using an envelope calculation and range from ±1.8 to ±4.0 kV. The fifth and seventh elements are intended for minor beam steering rather than for focusing. Insertable Faraday cups are located after the third and ninth elements.

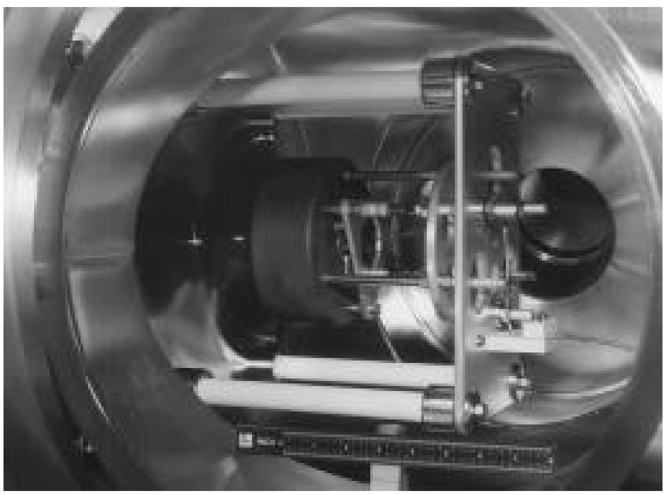


FIGURE 9. Interior of source tank, showing back of source and (at left) hole through which beam passes on its way into matching section. Holes of varying size can be used. (30-00-0695-1653pb01)

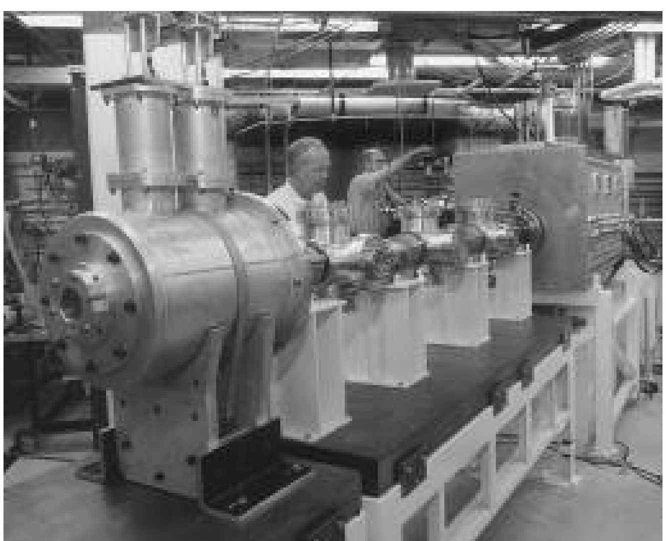


FIGURE 10. Straight transport section. Each spool holds two permanent-magnet quadrupoles; the entire section uses seven quadrupoles. The large enclosure at the left foreground contains diagnostic apparatus. (Orientation is opposite to that of Fig. 8, which does not show diagnostics enclosure.) (30-00-0695-1651pb01)

Figures 9 and 10 show some of the experimental apparatus. Figure 9 shows the source and diode. A potassium-impregnated zeolite element is heated by an internal filament; the beam passes through the hole visible at the left end of the anode–cathode gap. Figure 10 shows the linear transport section.

Time-resolved measurements of beam properties have been obtained at various locations throughout the matching and magnetic transport sections. The current has been measured using Faraday cups 0.67 and 1.9 m downstream from the diode source in the matching section and 3.16 m downstream in the magnetic transport section. An energy analyzer developed at LBL (consisting of curved electrostatic plates across which various potential differences are placed) was located 1.75 m downstream from the source. A two-slit scanner was placed at positions 0.2 and 1.6 m downstream from the source, providing measurements of emittance, beam radius, and beam centroid location.

Figure 11 shows an example of current vs time at the Faraday cup 1.9 m downstream from the diode source and corresponding results from the 1-D code HINJ[17]; there is close agreement between simulation and experiment. The large current spike at the head of the pulse arises because the rise time of the diode voltage (about 1 μs) is longer than the ideal rise time of 0.48 μs.[18] With the longer rise time, particles emitted at the beginning of the pulse have significantly lower energy than particles emitted later, so particle overtaking occurs. A modification of the pulser circuitry to reduce the rise time by a factor of two is planned. The code results are slightly noisier than those from the experiment; this results from a numerical deconvolution of the voltage waveform (to account for time lags in the voltage monitor), which introduces noise into the voltage waveform used by the code. Figure 12 shows a measurement of the horizontal normalized emittance at the end of the matching section. The high initial value appears to be due to the instantaneously high line-charge density.

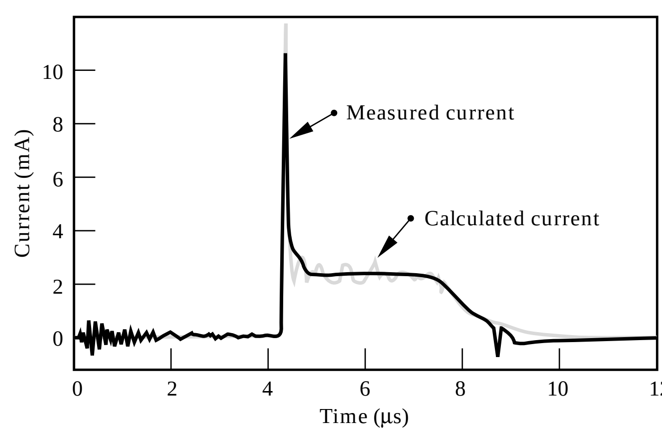


FIGURE 11. Current at the Faraday cup 1.9 m downstream of the diode source, and corresponding results from the 1-D code HINJ. (30-00-0695-1647pb01)

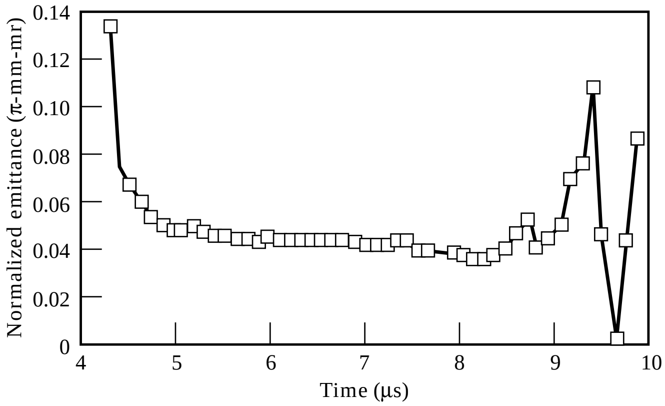


FIGURE 12. Measurement of horizontal normalized emittance at end of matching section. (30-00-0695-1648pb01)

Conclusions

The linear induction accelerator remains a very attractive Inertial Fusion Energy driver; the recirculator offers the promise of significant cost reduction, if the technical challenges of recirculation can be met. The LLNL Small Recirculator experiments are designed to provide a test bed for the necessary technology and to show that the beam dynamics in an induction recirculator are favorable; these experiments will pave the way to a larger-scale follow-on facility. These experiments, in conjunction with the ILSE experimental program at LBL and with detailed computer simulations, will lead to much more precise and credible predictions of heavy-ion driver behavior and cost and will allow the staged construction of the first IFE driver to begin shortly after ICF ignition is demonstrated on the National Ignition Facility.

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